Channeling 2018

First observation of the Grating Diffraction Radiation

[(a)] A. Potylitsyn, G. Naumenko, M. Shevelev, D. Shkitov, L. Sukhikh,

[(b)] A. Aryshev, N. Terunuma, J. Urakawa

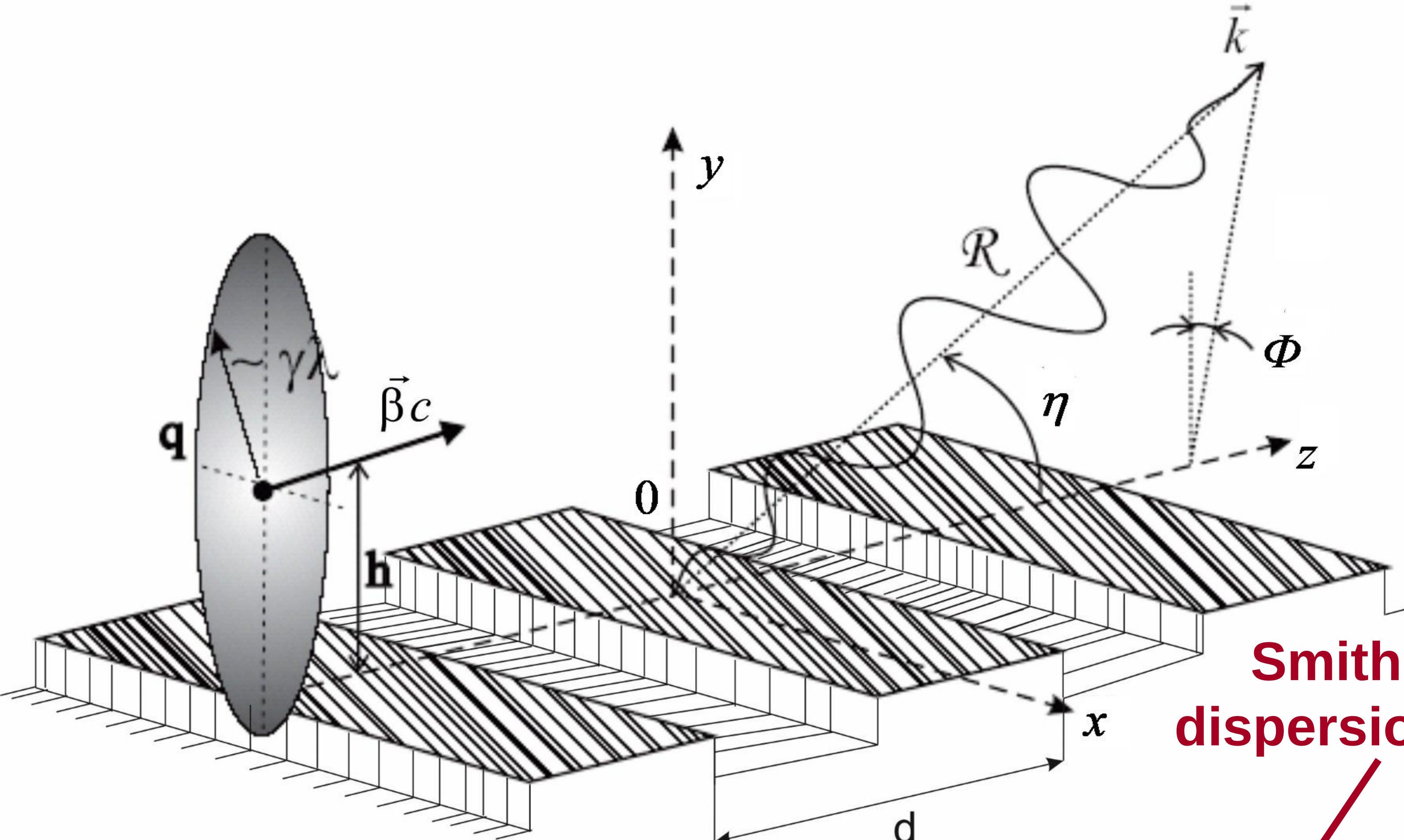
[a] TPU: Tomsk Polytechnic University

[b] KEK: High Energy Accelerator Research Organization

Content

- Linac-based THz sources provide sub-ps ~μJ radiation pulses with continuous spectrum;
- To obtain narrow-band spectral line with a possibility of the frequency tuning one should use a monochromator;
- Other possibility is to use SPR source with spectral line adjustment changing emission angle;
- Source based on Grating Transition Radiation (GTR) can provide line adjustment for fixed emission angle.

Smith- Purcell radiation (resonant diffraction radiation)



Far-field zone:

$R >> \gamma^2 \lambda$

$R >> Nd$

N – number of periods

Smith-Purcell dispersion relation:

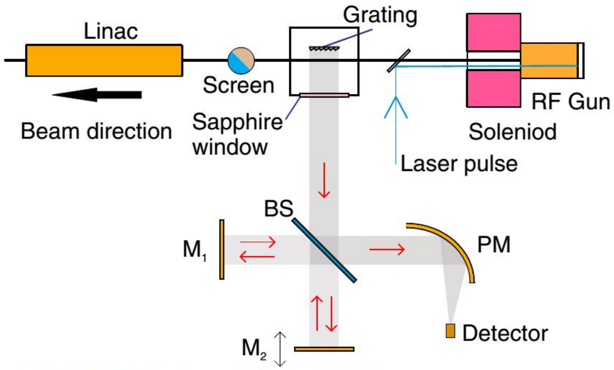
$$\lambda_n = \frac{d}{n}\left(\frac{1}{\beta} - \cos\eta\right)$$

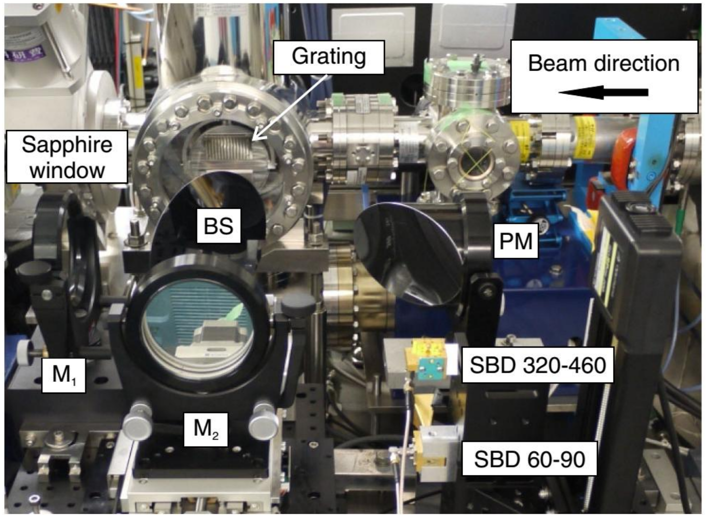
First observed by

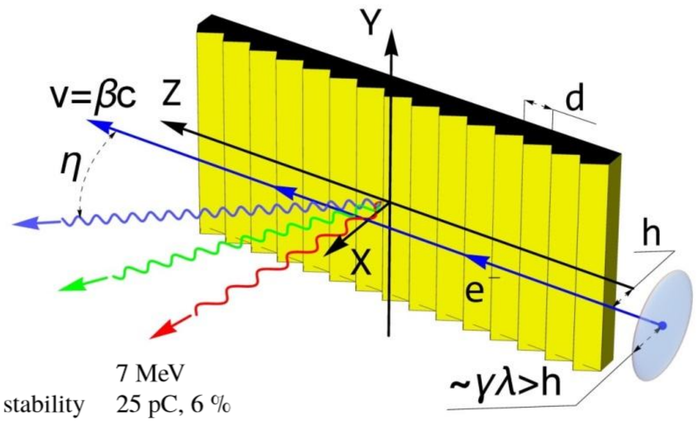
S.J. Smith and E.M. Purcell,

Phys. Rev. Lett. **92**, 1069 (1953))

SPR investigations at LUCX (KEK, Japan)







Beam energy, typ.	7 MeV
Micro-bunch charge Q and stability	25 pC, 6 %
Number of micro-bunches,	1,2,4
Bunch length, for given Q	250 fs
Normalized emittance, $\epsilon_x \times \epsilon_y$	1.5 × 1 πmm mrad

Top: experimental schematics
Bottom: photograph of the experimental station
Right: SPR target

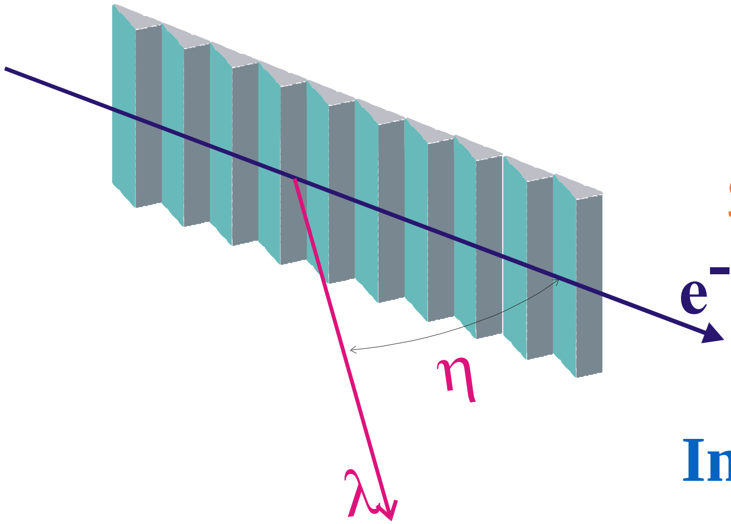
Abbreviations: M1 — fixed interferometer mirror, M2 — movable interferometer mirror, BS — splitter, PM — off-axis parabolic mirror

Michelson interferometer, see M. Shevelev et al. // NIM A 771, 126 (2015)

A. Aryshev et al. // PR-AB 20, 024701 (2017)

Detectors:
SBD 60-90 (ν = 60 ÷ 90 GHz)
SBD 320-460 (ν = 320 ÷ 460 GHz)

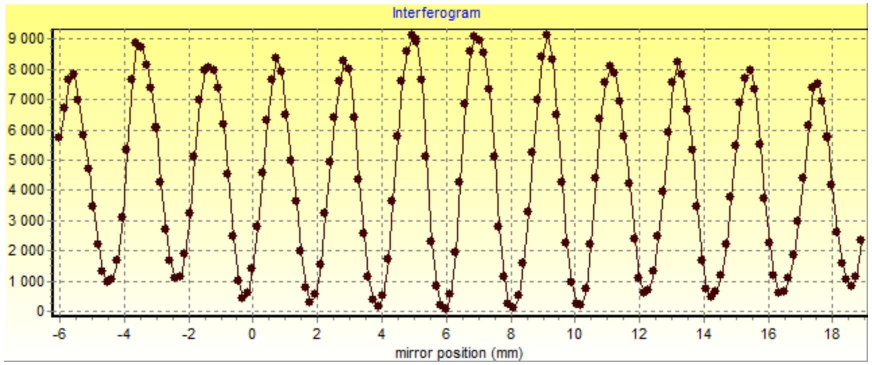
Smith-Purcell geometry



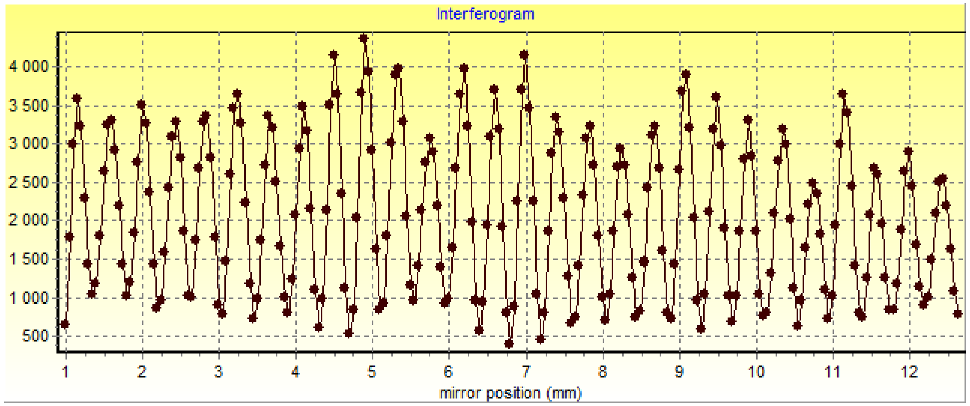
Smith Purcell geometry: $\theta = 0, \eta = 93.5°$

Interferograms

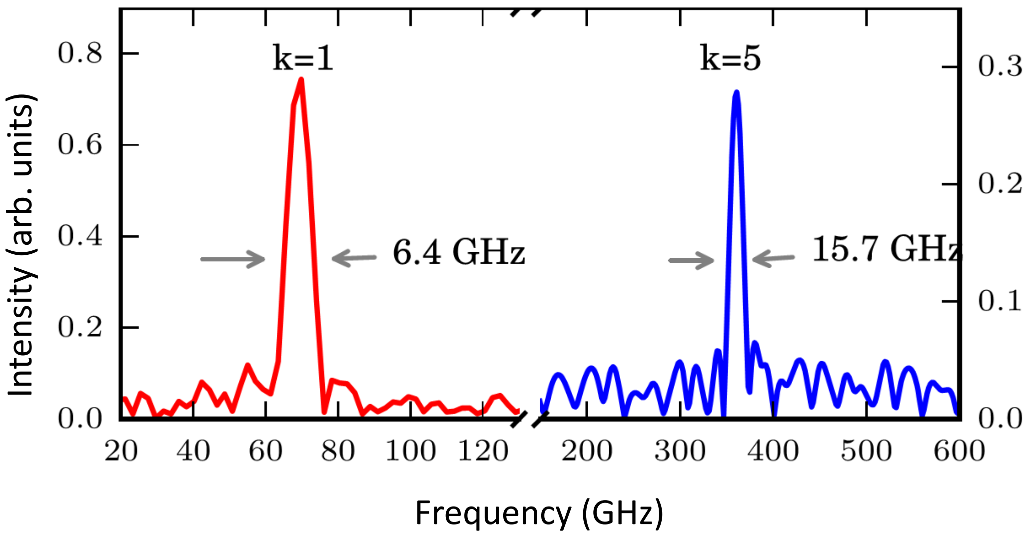
SBD_60-90



SBD_320-460



Coherent SPR spectral lines



SPR spectral measurements results

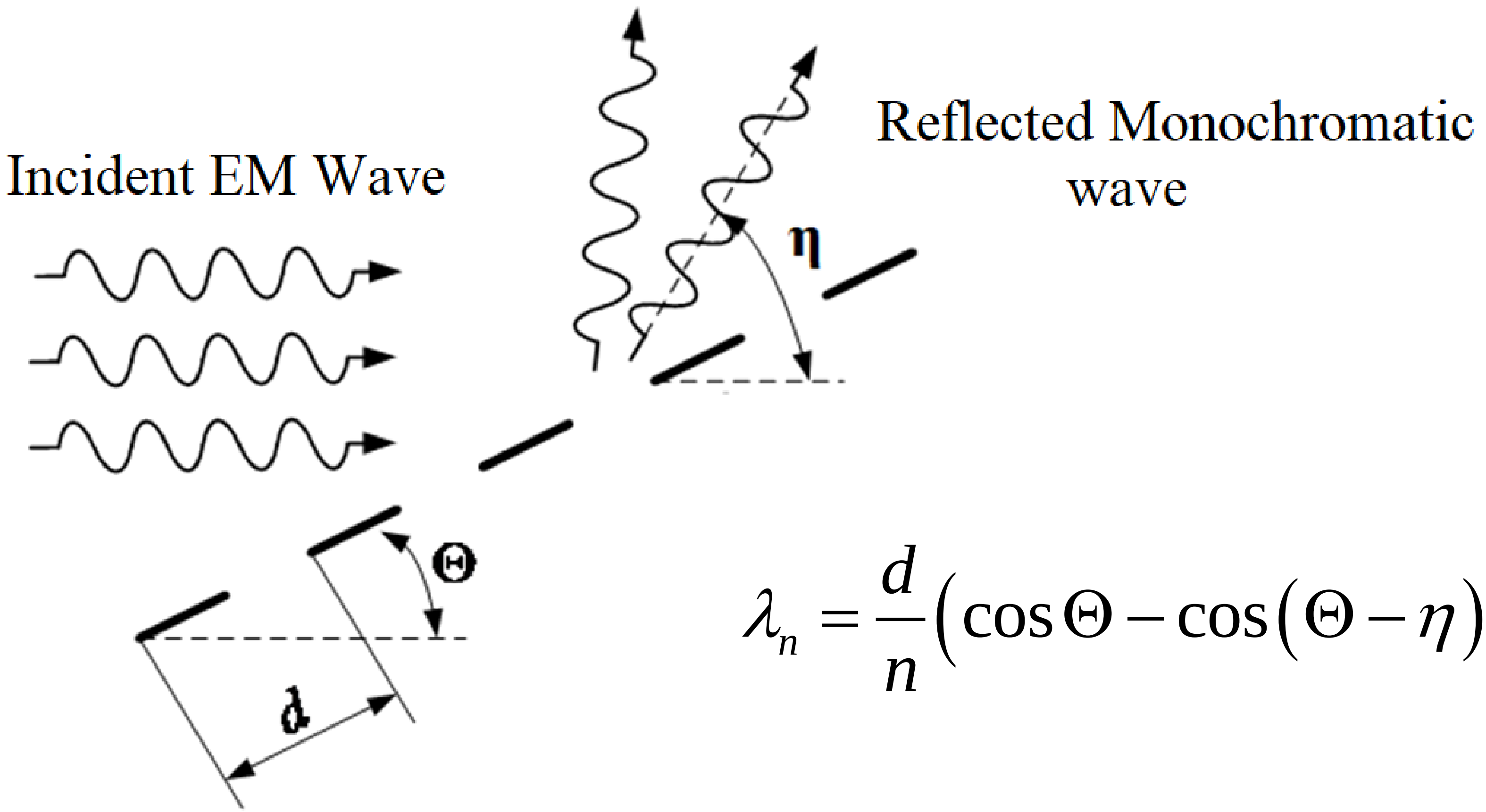
$$\frac{\Delta\nu_1}{\nu_1} \approx 9\% \qquad \frac{\Delta\nu_5}{\nu_5} \approx 4\%$$

Frequency resolution of Michelson interferometer:

$$\Delta\nu_{int} \sim \frac{c}{2L_{int}} \sim 5\ GHz$$

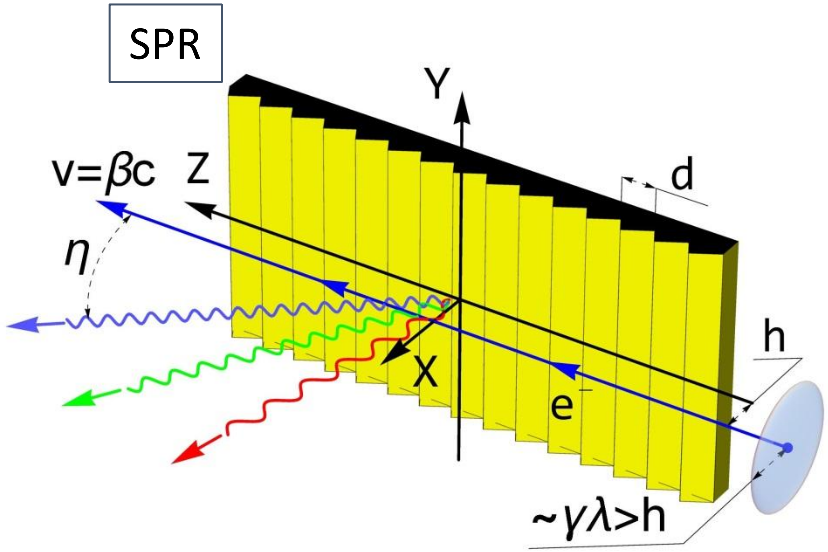
Line broadening is due to finite aperture

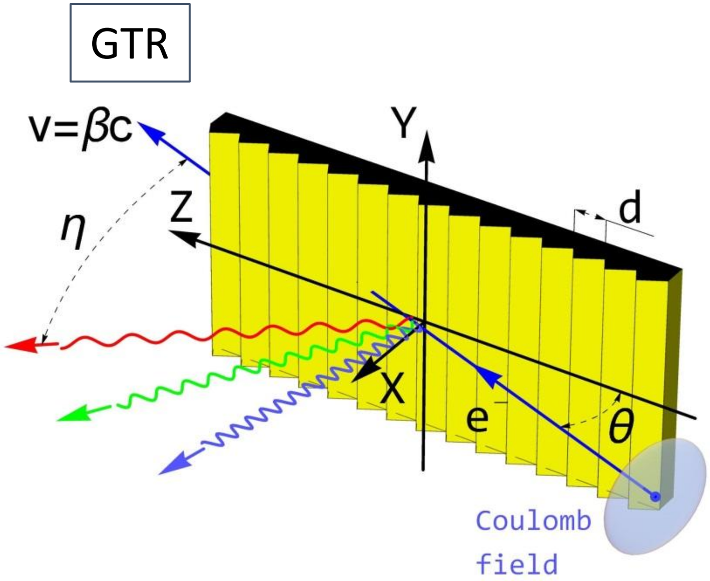
Reflection of the EM by a grating



$$\lambda_n = \frac{d}{n}\left(\cos\Theta - \cos\left(\Theta - \eta\right)\right)$$

Grating Transition Radiation





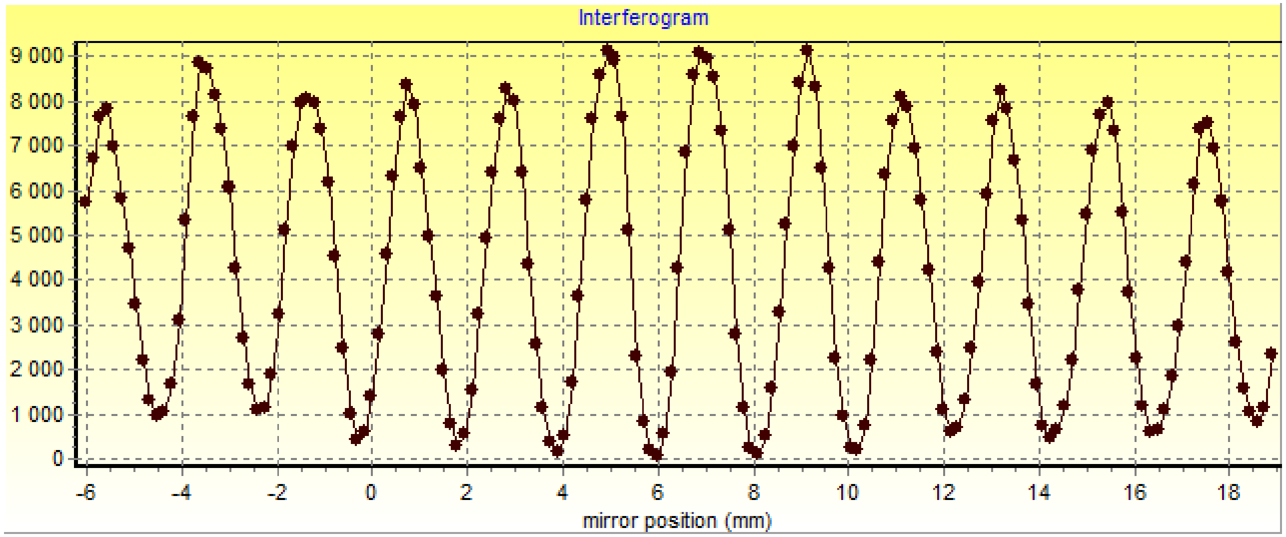
Dispersion relation:

$$\lambda_n = \frac{d}{n}\left[\cos\eta - \frac{1}{\beta}\right] \qquad \lambda_n = \frac{d}{n}\left[\cos(\eta-\theta) - \frac{\cos\theta}{\beta}\right]$$

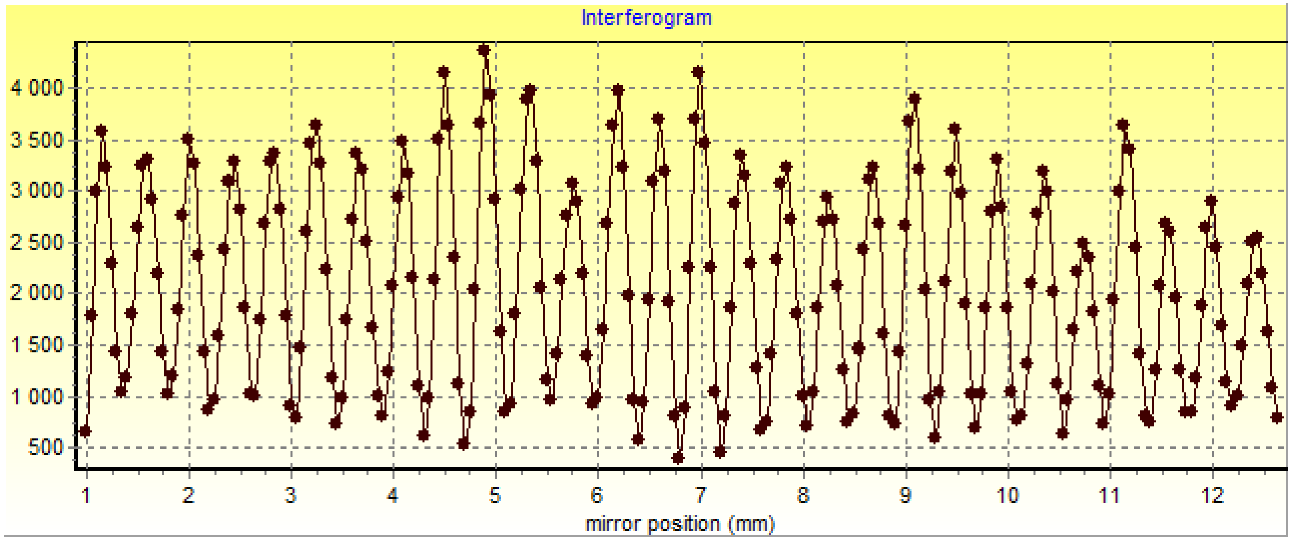
see, A.P. Potylitsyn et al. // Phys. Rev. E 61, 7039 (2000)

GTR monochromaticity is defined by overlapping of the Coulomb field and the grating
$\frac{\Delta\lambda}{\lambda} \sim \frac{1}{N_{eff}} \approx \frac{d \cdot sin\theta}{\gamma\lambda}$, if $N_{eff} \gg 1$

GTR Interferogram

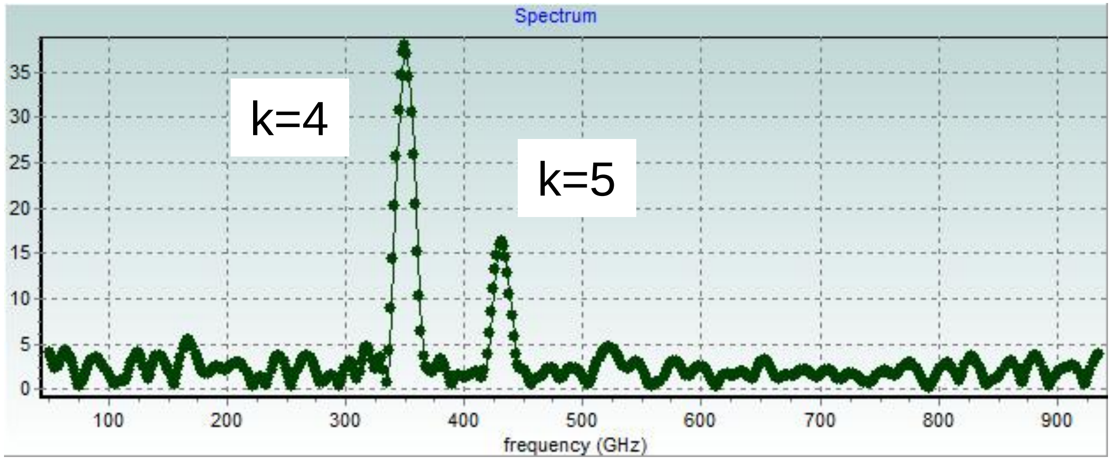


SBD_60-90

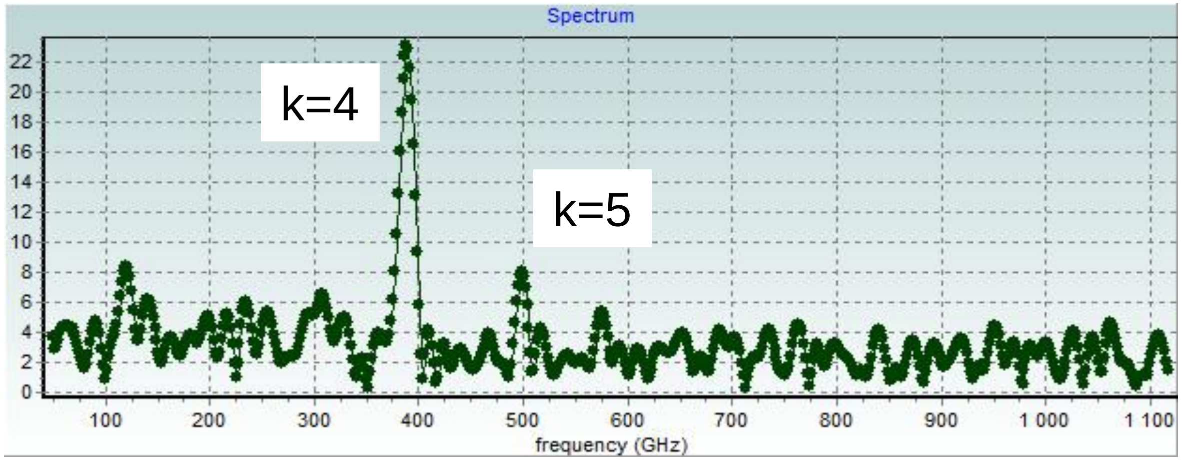


SBD_320-460

Spectra reconstruction (SBD 320-460)

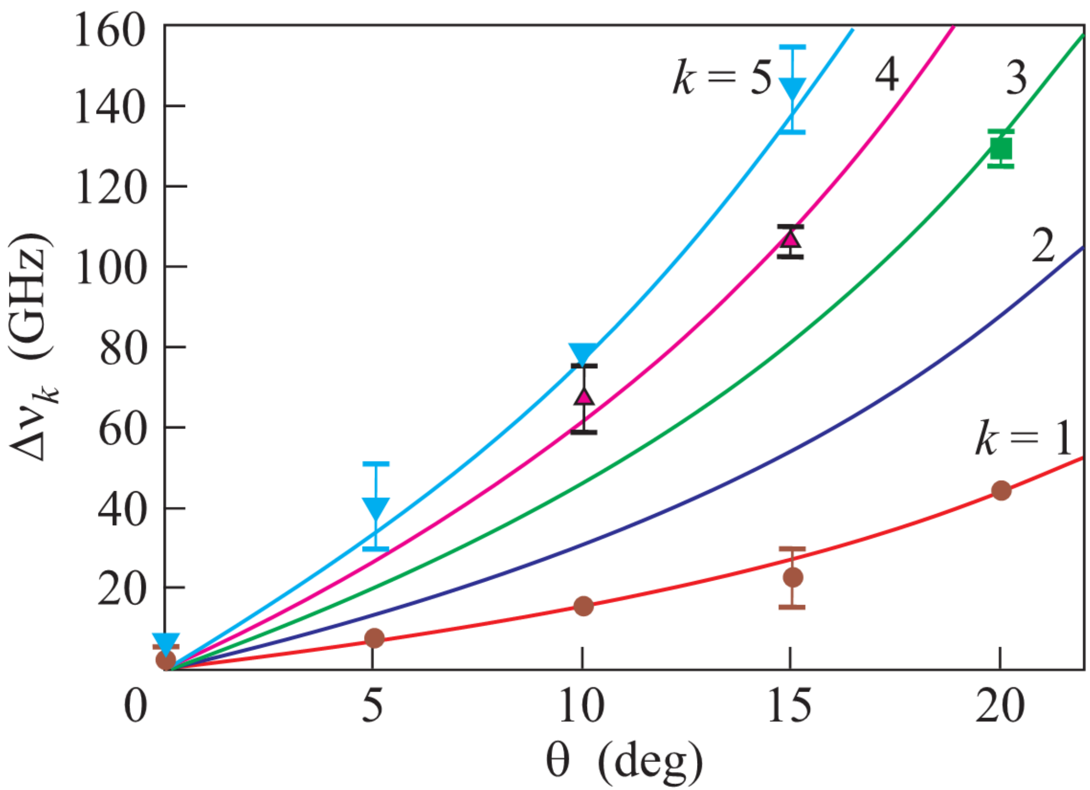


1 bunch
SBD 320-460
SBD att = 1 dB
θ = 10^0



1 bunch
SBD 320-460
SBD att = 5 dB
θ = 15^0

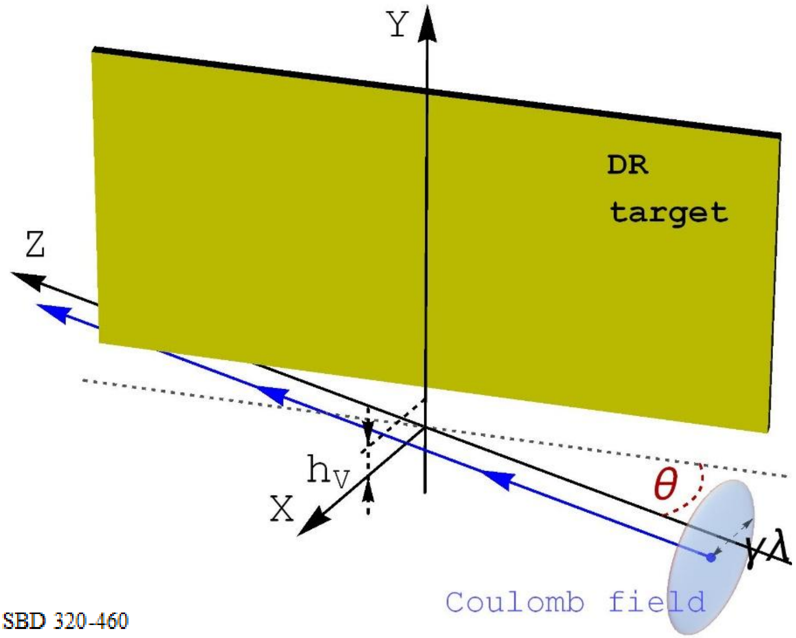
Confirmation of the dispersion relation

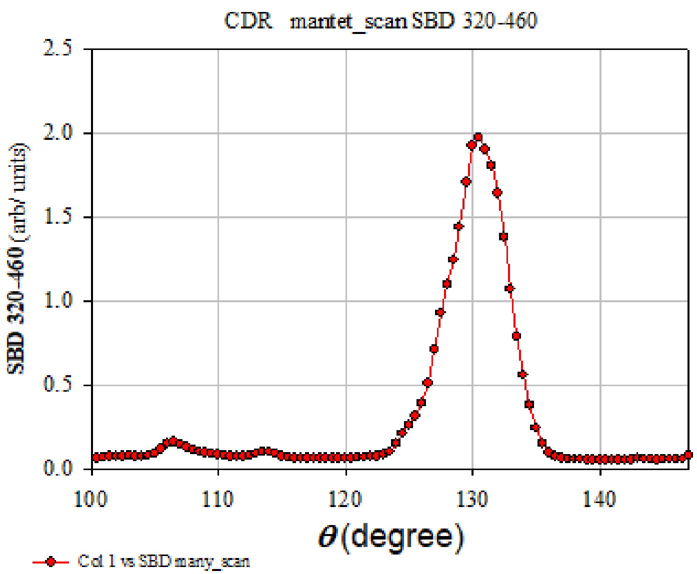


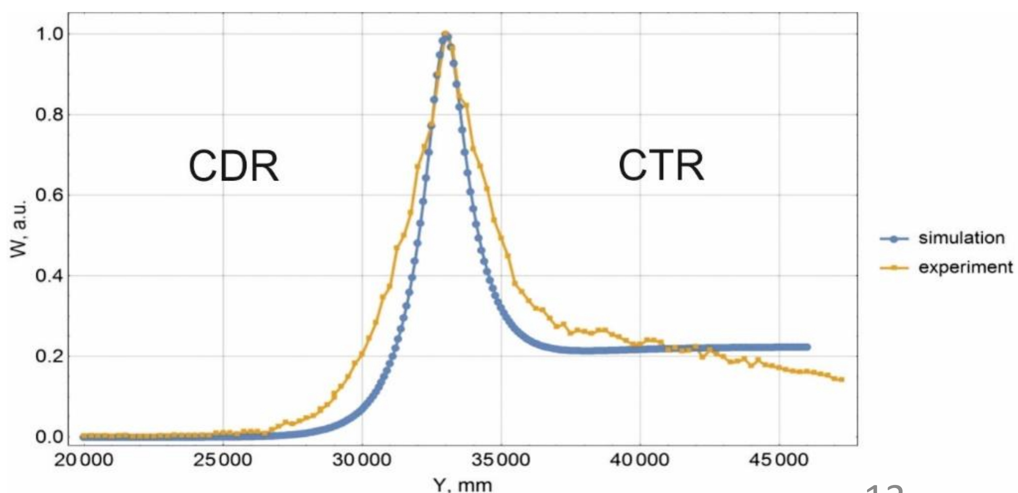
$$\eta = 93.5^o$$

Frequency shift of GTR lines from the Smith–Purcell frequency in comparison with an estimate from the dispersion relation

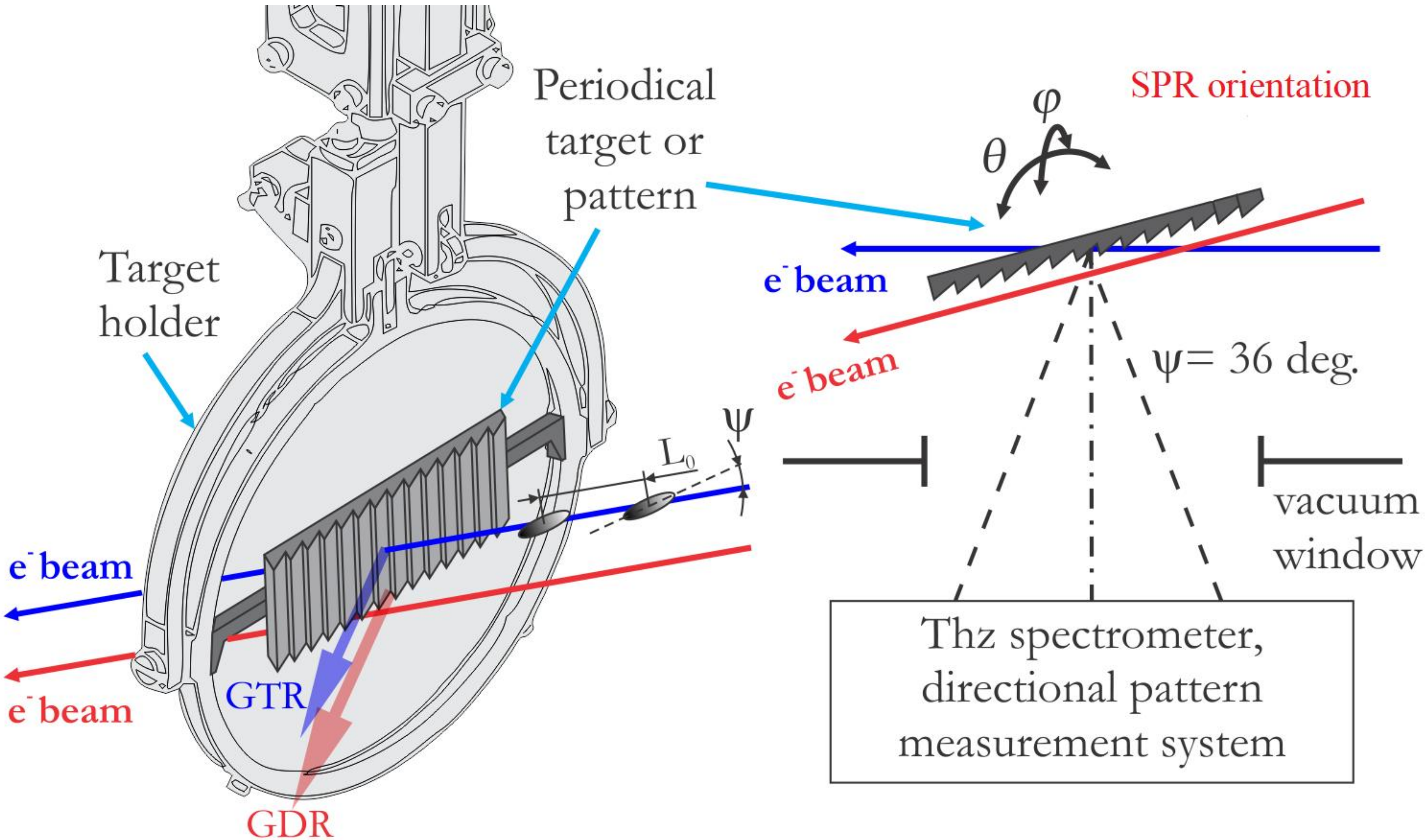
Coherent Diffraction Radiation



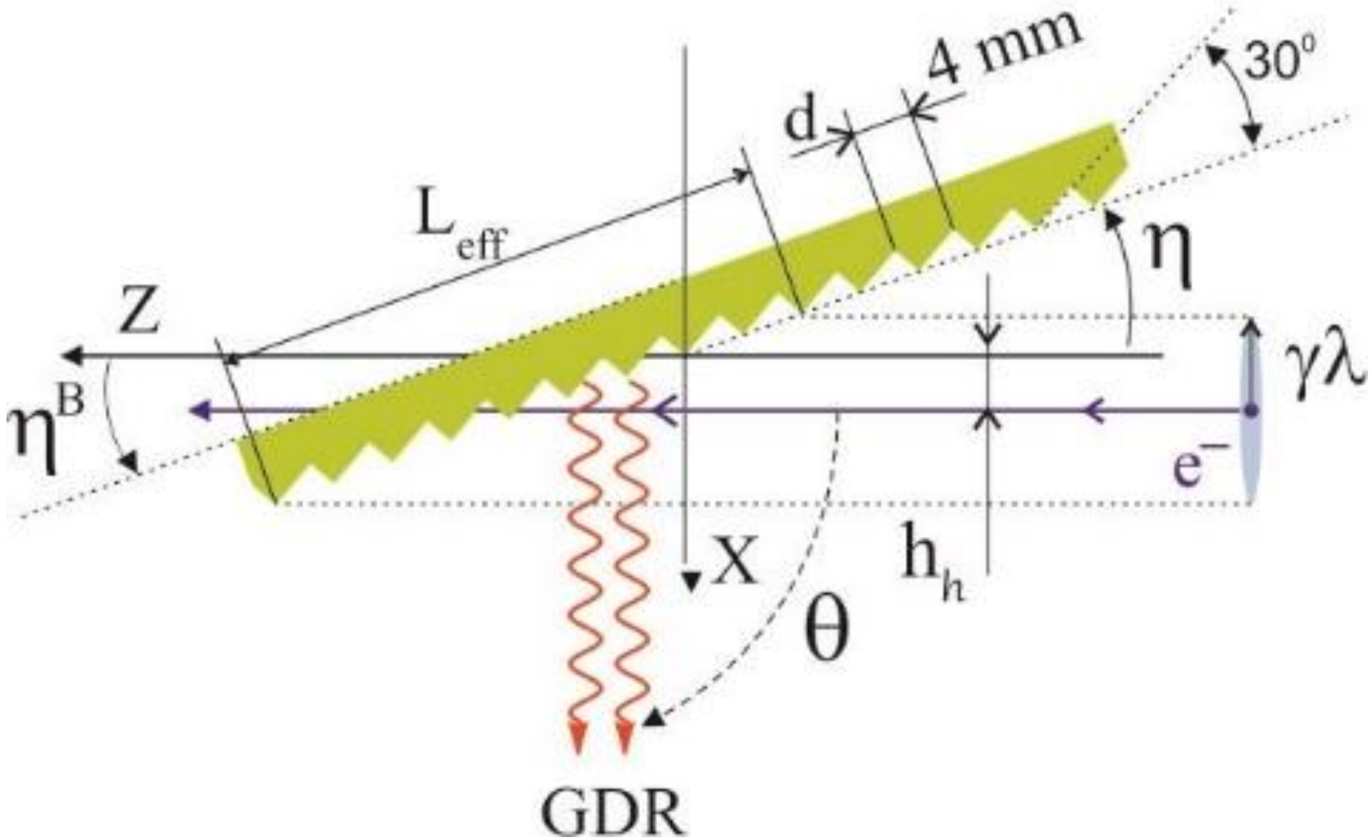




Geometry of the experiment

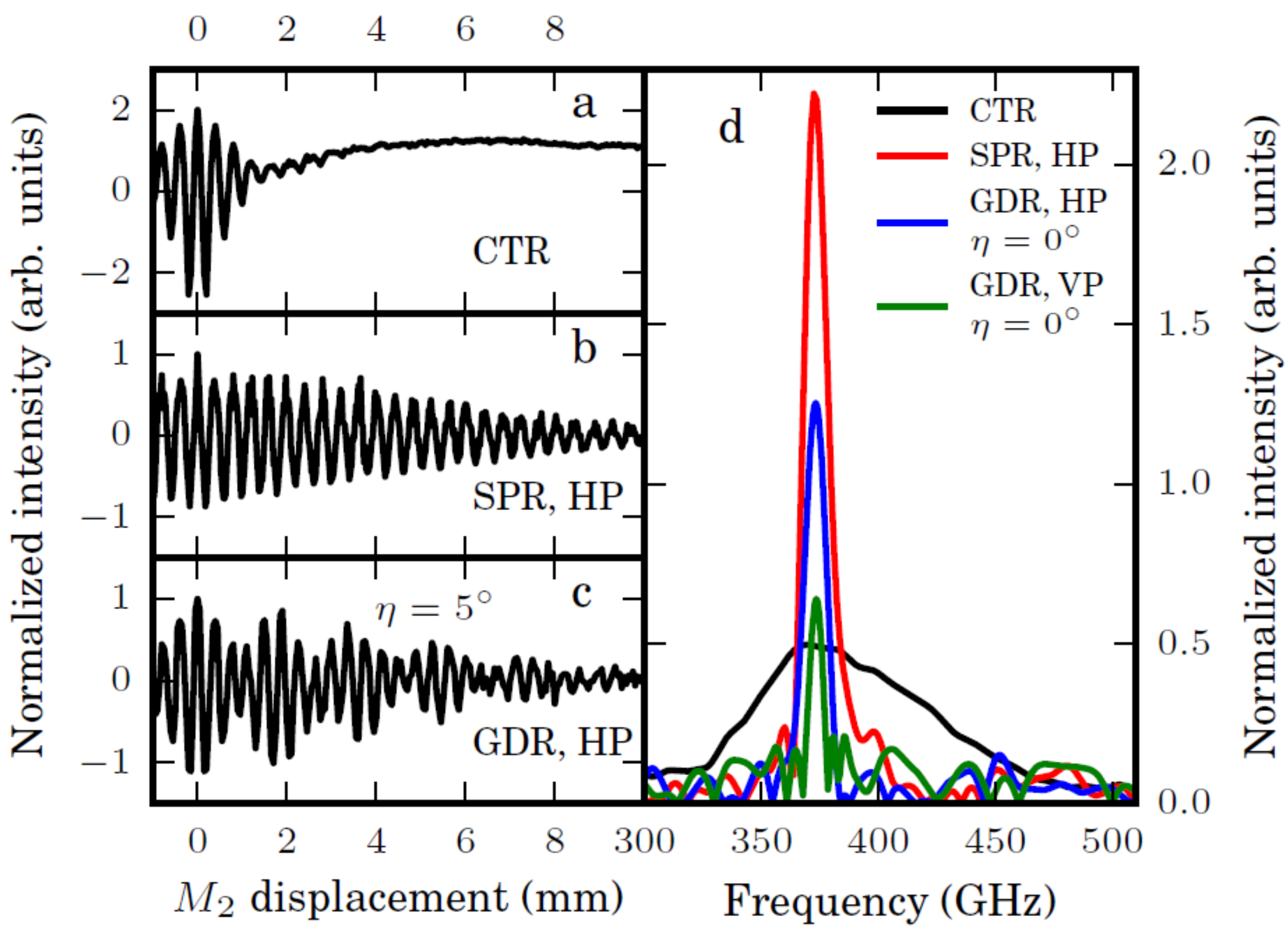


Grating Geometry

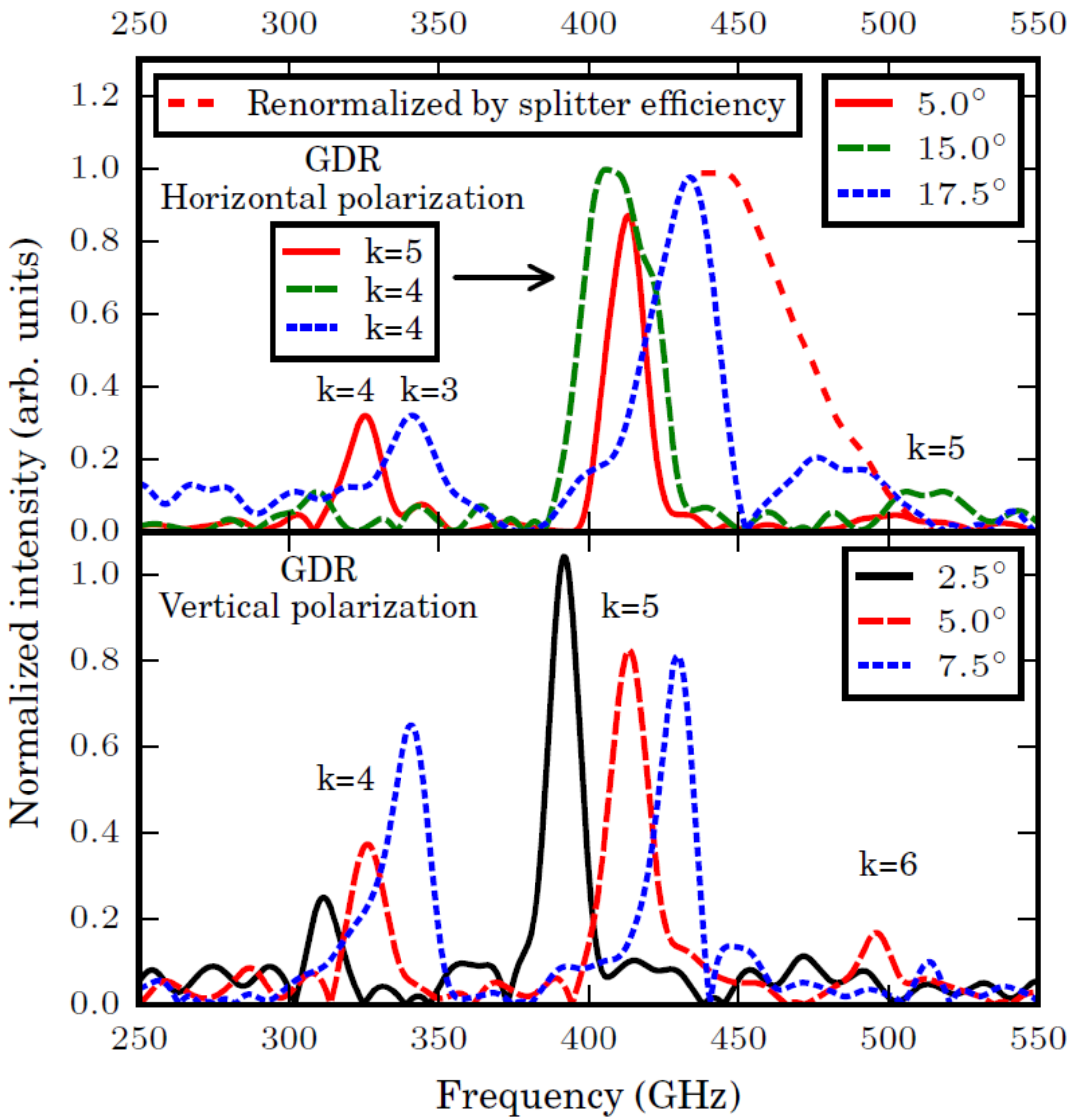


GDR monochromatisty $\frac{\Delta\lambda}{\lambda} : \frac{L_{eff}}{d} = \frac{d \sin\theta}{\gamma\lambda}$

GDR Spectral lines



GDR Spectral lines

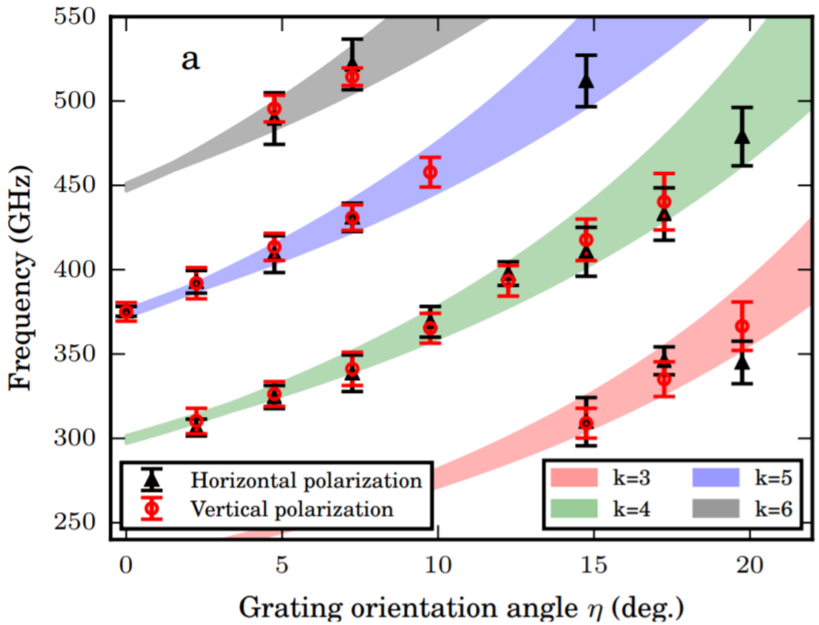


Zoom-in of the typical measured auto-correlation curves of: a - CTR, b - SPR, c - GDR, horizontal polarization and d - reconstructed spectra

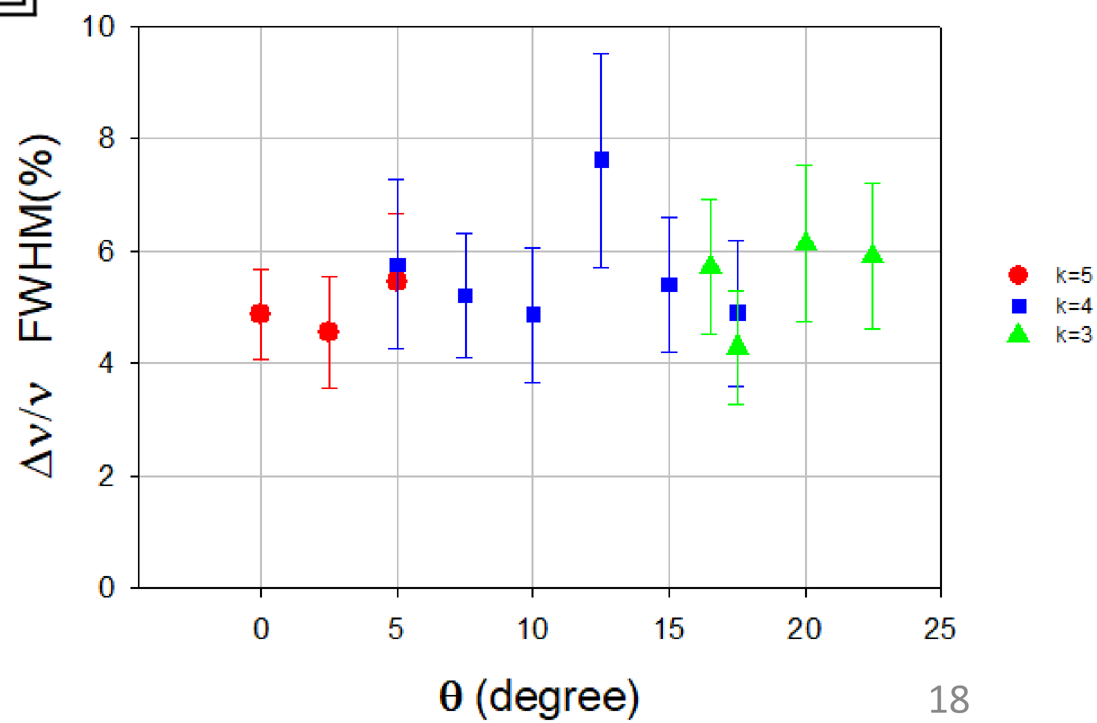
GDR dispersion relation:

$$\lambda_n = \frac{d}{n}\left[\cos(\eta - \theta) - \frac{\cos\theta}{\beta}\right]$$

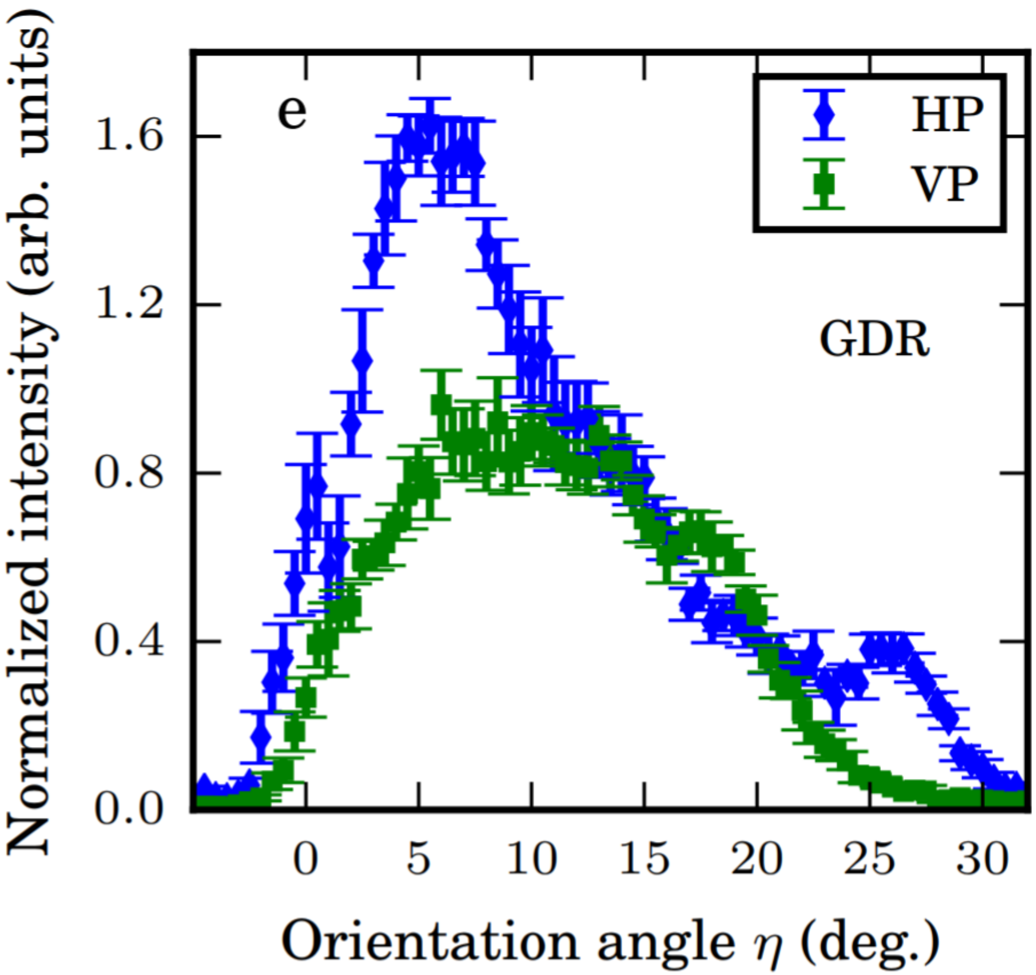
Peak Position



Line Width



GDR Polarization components



$$\Delta \nu = 320 - 460\, GHz$$

Calculation method

We used generalized surface current method to simulate GDR from the striped grating

$$E_R^D(r_D,\lambda) = \frac{1}{2\pi}\iint \left[\left[n(r_T), E_e^T(r_T,\lambda)\right], \nabla G(r_T,r_D,\lambda)\right] dS_T$$

$$E_e^T(r_T,\lambda) = \frac{2e}{\beta^2 c\gamma\lambda}\cdot e^{i\frac{k}{\beta}z_T}\cdot\begin{Bmatrix} \frac{x}{\sqrt{x_T^2+y_T^2}}K_1\left(\frac{k}{\beta\gamma}\sqrt{x_T^2+y_T^2}\right) \\ \frac{y}{\sqrt{x_T^2+y_T^2}}K_1\left(\frac{k}{\beta\gamma}\sqrt{x_T^2+y_T^2}\right) \\ -\frac{i}{\gamma}K_0\left(\frac{k}{\beta\gamma}\sqrt{x_T^2+y_T^2}\right) \end{Bmatrix}$$

$$\nabla G(r_T,r_D,\lambda) = \frac{r_D - r_T}{|r_D-r_T|^2}\cdot e^{ik|r_D-r_T|}\cdot\left(\frac{1}{|r_D-r_T|} - ik\right)$$

$$n(r_T) = A(\psi).\{0,0,1\}$$

$$\frac{d^2W_e}{d\omega d\Omega} = cr^2\left|E_R^D(r_D,\lambda)\right|^2$$

Where $r_T = \{x_T, y_T, z_T\}$ and $r_D = \{x_D, y_D, z_D\}$ are the coordinate on the target and detector surface respectively, λ is the radiation wavelength, $k = 2\pi/\lambda$ is the wave number, $|r_D - r_T|$ is the distance between the points on the detector and the target, $A(\psi)$ is the rotation matrix for the normal vector at ψ angle for each strip in the target, S_T is the target surface and E_e^T is the electron coulomb field, E_R^D is the radiation field.

D. V. Karlovets, A P. Potylitsyn, Generalized surface current method in the macroscopic theory of diffraction radiation // PLA 373 (2009) 1988

Simulation scheme

I. Number of strips (From 1 to 15 strips in “0” for λ)

II. Different polarization components of GDR

III. Observation point → detector aperture (Different obs. point Z = -5, 0 and 5 mm)

IV. Spatial distributions (3D distribution and 2 sections (along Z and Y) for λ)

V. Target tilting angle (From -25˚ to 60˚ in “0” for λ and spectra)

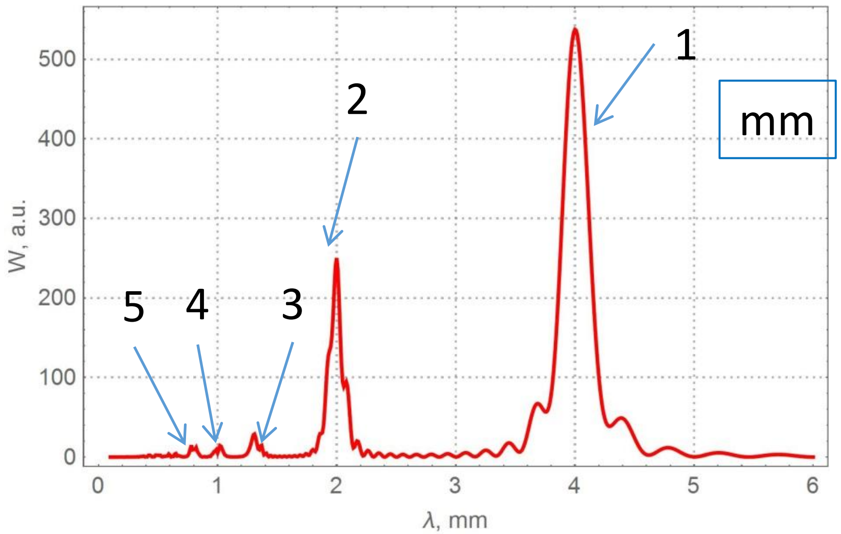
VI. Target tilting angle for two detectors (From -5˚ to 29˚ in “0”)

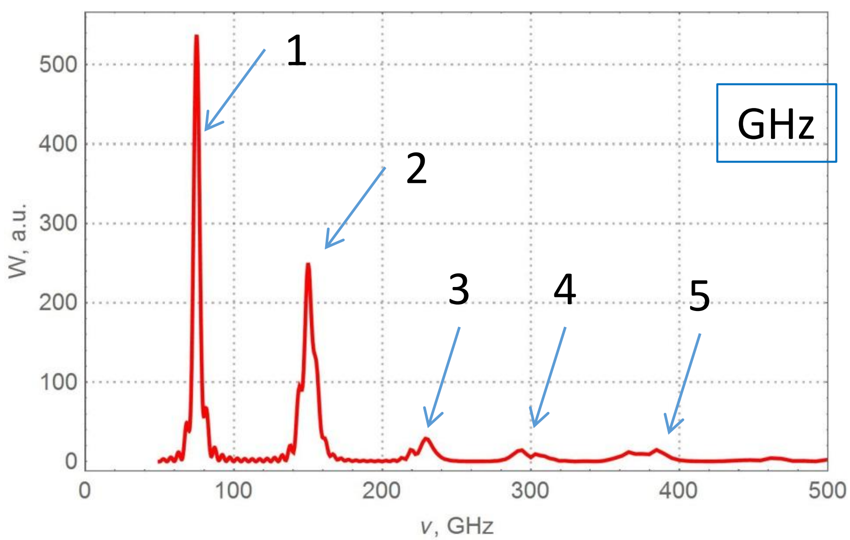
VII. Electron energy → energy spread (Spectra for 8.25 MeV ± 1% (8.1675 MeV , 8.3325 MeV))

VIII. Bunch length → coherence (Single case)

IX. Micro-train (for 2 bunches with different distance between them)

Spectrum simulation

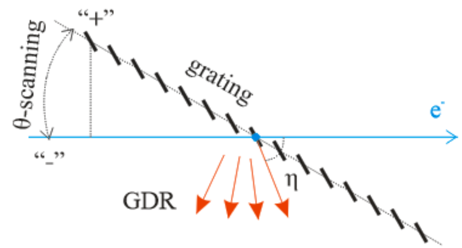




8.25 MeV
θ = 0˚
η = 90˚
Z, Y = 0
15 strips
d = 4 mm

Spectrum in terms of wave length and frequency at 90˚ to the target.

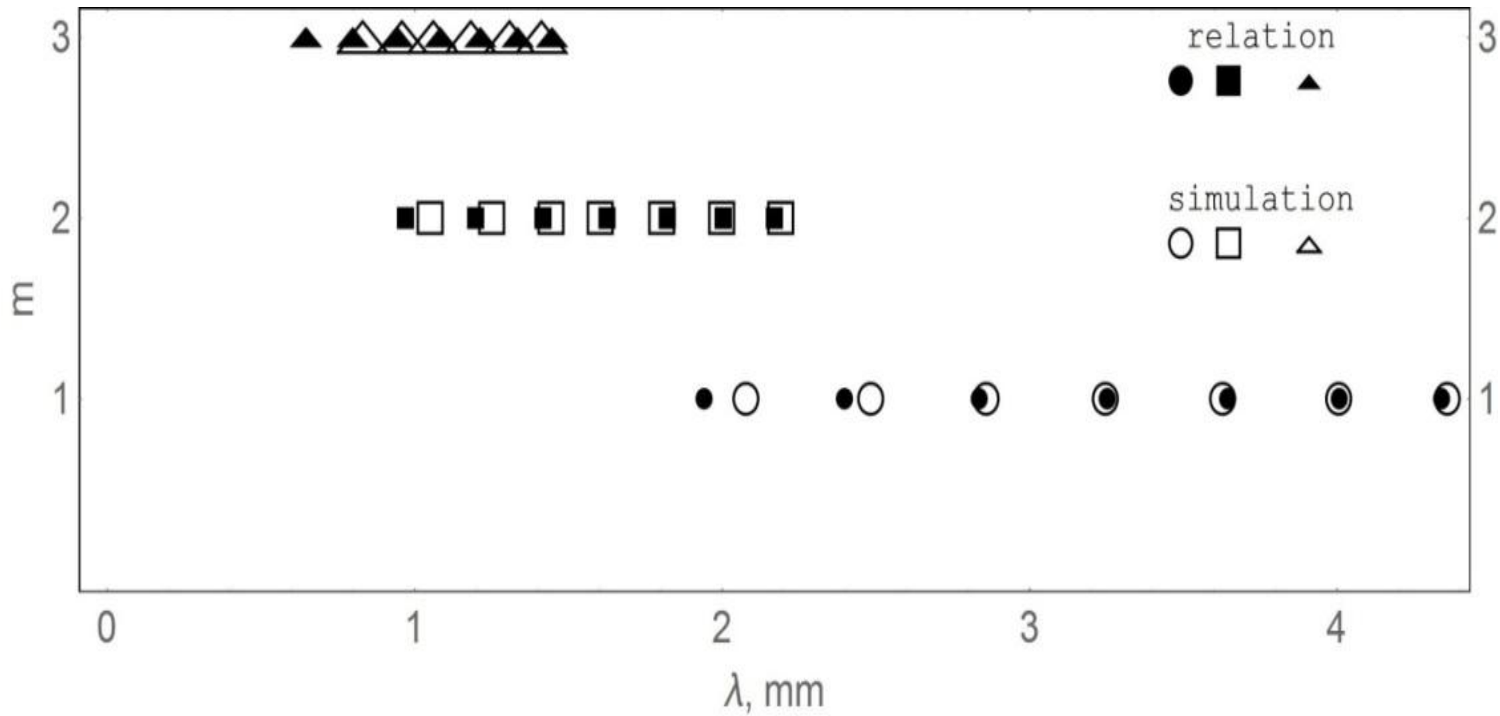
Peaks positions correspond to the dispersion relation.



$$\lambda_m = \frac{d}{m} \cdot \left(\frac{cos\theta}{\beta} - \cos(\eta - \theta) \right)$$

m	~λ, mm	~ν, GHz
1	4	75
2	2	150
3	1.33	225
4	1	300
5	0.8	375
~~**6**~~	~~0.66~~	~~450~~
~~**7**~~	~~0.57~~	~~525~~

Comparison of peak position from the simulation and dispersion relation



The comparison of peak position which derived from the simulation and dispersion relation is presented. We may see that the comparison is in good agreement. Main reason of discrepancies between simulation and dispersion relation is that the relation was obtained in the far field approximation when simulation was performed for certain distance to the observation point

SUMMARY

- We have observed GDR in the sub-THz range and confirmed the dispersion relation depending on two angular variables (θ, η);
- Monochromaticity of GDR ${}^{\Delta\nu_k}/_{\nu_k}$ depends on the diffraction order *k* and coincides practically with the SPR monochromaticity;
- Intensity of GDR is comparable with intensity of SPR for the grating rotation angles $\theta = 0 \div 20^{\circ}$ and spectral line shift $\sim 20 \div 25\%$.
- In contrast with conventional SPR there exist two polarization components in GDR

Thanks for attention!